Predicting the Performance of Concrete Repair Materials

Summary of Workshop
April 26 and 27, 1999
Durham, New Hampshire

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NIST

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Workshop Sponsors:
    Conproco Corp.
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ABSTRACT

On April 26 and 27, 1999 a workshop on *Predicting the Performance of Concrete Repair Materials* was held at the New England Conference Center in Durham, New Hampshire. This workshop was a follow up of a previous workshop held in 1995 at the National Institute of Standards and Technology which dealt with research needs to minimize cracking in concrete repair materials. The focus of the 1999 workshop was on test methods and modeling techniques for predicting the performance of concrete repairs. The two-day workshop included a half-day of presentations to define the problems and review current knowledge. The presentations were followed by working group sessions on the following topics: (1) modeling material performance; (2) repair design, specification, and application; and (3) repair materials and systems. The conclusions of the working groups were presented at a plenary session on the second day. The workshop concluded with recommendations for action. This report provides summaries of the working group discussions and concludes with the recommended actions.

Keywords: Building technology; concrete repair; drying shrinkage; modeling; performance criteria; tensile creep; tensile strength; test methods.

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ACKNOWLEDGEMENTS

It would be inappropriate to conclude without acknowledging that the success of this workshop, and the interest generated thereby, were due in large part to the attendees themselves who participated enthusiastically during the working group sessions.

1. INTRODUCTION

1.1 Cracking of Repair Materials

The concrete industry of the 21st Century is facing two major challenges:

- How to design and construct new concrete structures that will perform during their design service life with minimum maintenance and repair; and
- How to maintain the desired service life of distressed or deteriorated existing concrete structures; how to rehabilitate, repair, and protect them so they continue to serve their intended purpose.

The performance of a repaired concrete structure, and thus its service life, depends on the quality of the composite system formed by the repair material and the existing concrete substrate. The behavior of these two components must be compatible if the repaired structure is to maintain its integrity. Compared with other characteristics, the absence of cracking of the repair phase has a major impact on the long-term durability of a repair system. While development of tensile cracks may be favorable from the point of view of stress distribution in the repair material, the situation is different when judged from the point of view of the permeability of the material—its ability to retard penetration of aggressive elements into the concrete.

Cracking in the repair phase, caused by restrained volume changes, is one of the most common causes of poor performance in repaired structures. Cracking initiates and promotes corrosion, especially in severe environments, and corrosion, in turn, causes enlargement of cracks. Increased cracking aggravates any one of a number of other mechanisms of deterioration. For example, in repeated cycles of freezing and thawing in a wet environment, water enters the cracks during the thawing portion of the cycle and, during subsequent freezing, the expansive stress results in progressive deterioration.

The sensitivity to cracking of repair materials used in a repair project is one of the most critical factors affecting the durability of the repaired structure. It must be emphasized, however, that repair problems cannot be resolved simply by specifying and using crack-resistant repair materials. Evaluation of existing concrete conditions, design details and specifications, and quality of on-site workmanship are also of fundamental importance in ensuring durability of repaired structures.

The intent of the workshop summarized in this report was to examine the tools needed by the repair industry to ensure that materials specified and used for concrete repairs are dimensionally compatible with existing concrete substrates so as to minimize cracking during the desired service life. The workshop focused on modeling techniques for predicting the service life of concrete repairs, and on test methods and performance criteria for selecting repair materials with low likelihood of cracking in service.

1.2 Workshop Objectives and Format

At the September 1995 workshop, "Research Needs for Establishing Material Properties to Minimize Cracking in Concrete Repairs" (Vaysburd 1996), held at the National Institute of Standards and Technology (NIST), the following needs were identified for the concrete repair industry:

- The need to enhance our understanding of causes and properties affecting cracking in repairs;
- The need for reliable prediction of performance of concrete repairs based on short-term tests; and
- The need for developing mathematical models for predicting the future service life of concrete repairs.

The workshop outlined the necessary research to be conducted to transform concrete repair from "art" to a technology based on engineering and material science. It was recommended that the workshop process be continued on a regular basis in order to improve the quality of the North American concrete repair industry and increase its international competitiveness.

The steering committee of the second workshop, "Predicting the Performance of Concrete Repair Materials," was composed of the following individuals:

- Christopher Brown, Conproco, Corp. (Chairman)
- James McDonald, U.S. Army Corps of Engineers (USACE) (Co-chairman)
- Noel Mailvaganam, National Research Council of Canada (NRC-CNRC) (Co-chairman)
- Douglas Burke, Naval Facilities Engineering Service Center
- Nicholas Carino, NIST
- Terence Holland, Consultant
- Dennis Pinelle, Conproco, Corp.
- Alexander Vaysburd, Structural Preservation Systems, Inc.

The workshop was held at the New England Hotel and Conference Center, Durham, New Hampshire on April 26 and 27, 1999. It was co-sponsored by the International Concrete Repair Institute (ICRI), the National Institute of Standards and Technology, the National Research Council of Canada, Conproco Corp., Structural Preservation Systems Inc., Master Builders Inc., Sika Corp., and W.R. Grace & Co. The workshop program and a list of the participants are included in Appendices A and B, respectively.

The objectives of the workshop were as follows:

- To review current methods for determining the service life of repair systems;

- To identify new studies, new test methods, and data needed to develop guidelines for determining the service life of repairs;
- To adopt or develop performance criteria for the selection of repair materials;
- To adopt or develop standard protocol for repair material data sheets;
- To reach agreement on how to develop a reliable model to predict the service life of concrete repairs; and
- To recommend actions necessary to develop the model.

To achieve these objectives, the 1999 workshop was arranged according to the following format:

- Attendance was by invitation in order to obtain a balance among material manufacturers, researchers, structural engineers and specifiers, constructors, and those working on mathematical modeling of material performance.
- The workshop started with a General Session where problem-statement papers were presented as indicated in the Program (Appendix A). The presentations were given by individuals actively involved in significant work. These papers were intended to give the latest information and points of view on the subject of cracking of repair materials.
- The workshop participants were divided into three working groups reflecting the participants' expertise and interests.

  - Group 1: Modeling Material Performance;
  - Group 2. Repair Design, Specification and Application (Users of repair materials);
  - Group 3. Repair Materials and Systems (Material manufacturers and researchers).

  Each working group had a chairman (or facilitator) and co-chairman as indicated in Appendix B. All discussions took place in working groups. Subsequent to the group discussions, the chairman and co-chairman of each working group prepared a summary report for the plenary session.
- The Workshop was concluded with a final discussion and recommendations for action.

The remainder of this report is based upon discussions and conclusions of the working groups. Chapter 2 summarizes the working group discussions; Chapter 3 lists the recommended action items; and Chapter 4 includes pertinent references.

The authors have exercised their prerogatives to limit the length of this summary. Much of the original floor discussions are omitted and only those items of direct significance to the objectives of this workshop are summarized.

2. WORKING GROUP REPORTS

2.1 Working Group 1 — Modeling Material Performance

Objectives
The group's discussion focused on answering the following questions:
- What are we trying to model?
- What is the uncertainty in analytical results?
- Who are the users of these analytical models?
- What models are available?
- What action items should be recommended to advance our modeling capabilities?

Purpose of Modeling
The ultimate objective of modeling is to be able to estimate the service life of the repaired concrete structure. However, this is a difficult problem, and it was the consensus of the group that this long-term objective will be achieved by incremental advances in our modeling capabilities. Therefore, it was decided to consider the requirements for three levels of models:

Level 1 —Evaluate the susceptibility of a given repair material to cracking under standardized conditions. This might serve as a screening tool for comparing the performance of alternative materials.

Level 2 —Predict the "short-term" performance of a specific repair under anticipated field conditions.

Level 3 —Predict the service life of repaired structures.

These are discussed in more detail.

Level 1 model—The objective of this model is to evaluate the susceptibility to cracking of a given repair material under standard (isothermal) conditions of restraint and drying. Basically, this model estimates the increase of restraint-induced tensile stress in the test specimen as a function of time and compares that stress with the developing tensile strength. The strength-to-stress ratio would be a measure of the likelihood of cracking under the given conditions. A value significantly *greater than 1* would indicate low likelihood of cracking, and a value significantly *less than 1* would indicate a high likelihood of cracking. Figure 1 is a schematic to illustrate hypothetical results for three materials: A, B, and C. In this example, material A would have the greatest cracking tendency, while material C would have the least. For each material, the strength-to-stress ratio is shown as a band to reflect the uncertainty of the analysis. One of the challenges in the development of a Level 1 model will be to determine how to represent the uncertainty in the results.
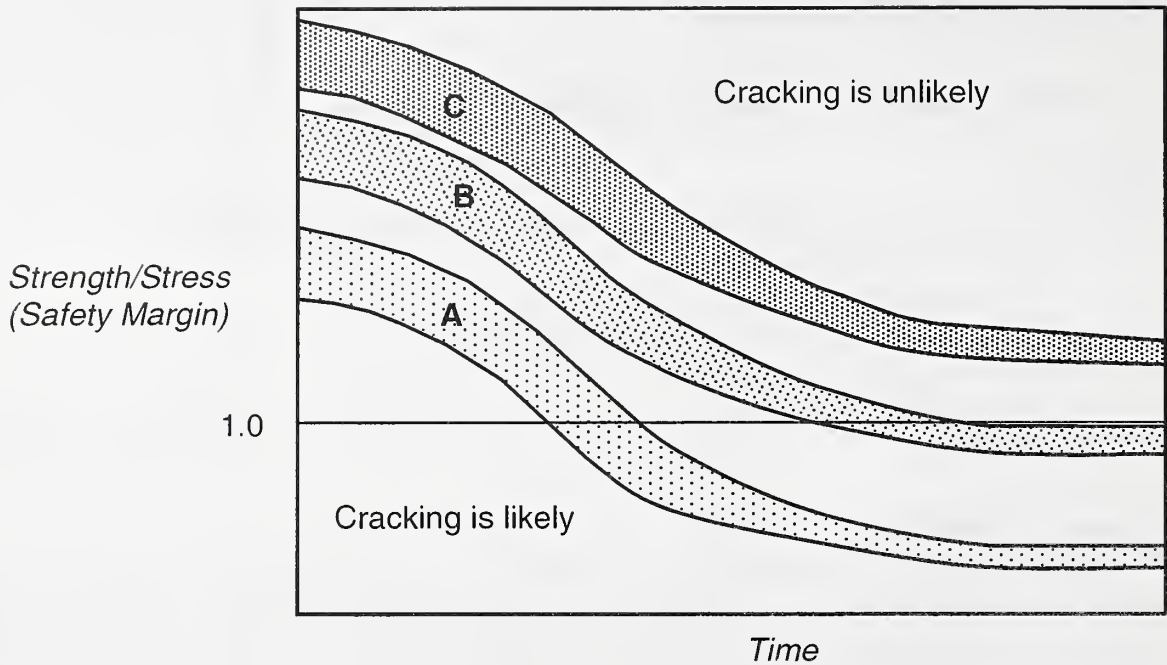
Figure 1   Schematic of strength-stress ratio as a function of time for specimens of three repair materials subjected to standard conditions of restraint and drying

To implement a Level 1 model requires knowing the following information about the repair material:

- The development of the elastic modulus;
- The development of tensile strength; and
- The development of autogenous shrinkage and drying shrinkage.

In addition, it is necessary to account for stress relaxation, which is beneficial in reducing the tensile stress that develops under restrained shrinkage. Standard test methods will be required to measure these basic properties of the material. A key question that needs to be answered is whether the stress relaxation (or creep) properties under tensile loading are significantly different from those under compressive loading. The answer to this question will dictate the complexity of the testing needed to measure the key properties. The measurement of these properties has to begin at early ages that correspond to when volume reductions would begin to occur (drying shrinkage and autogenous shrinkage) in the test specimen. Another important characteristic that must be understood is the tensile strength of the repair material under sustained stress. There are indications that the sustained strength may be a fraction of that measured in a short-term tensile test (Poston et al. 1998).

An important aspect of model development is the verification of the results by comparison with carefully controlled tests that replicate the analytical conditions. Two types of restrained shrinkage conditions might be considered. One involves axial

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(a) Axial restraint of prism

Repair material

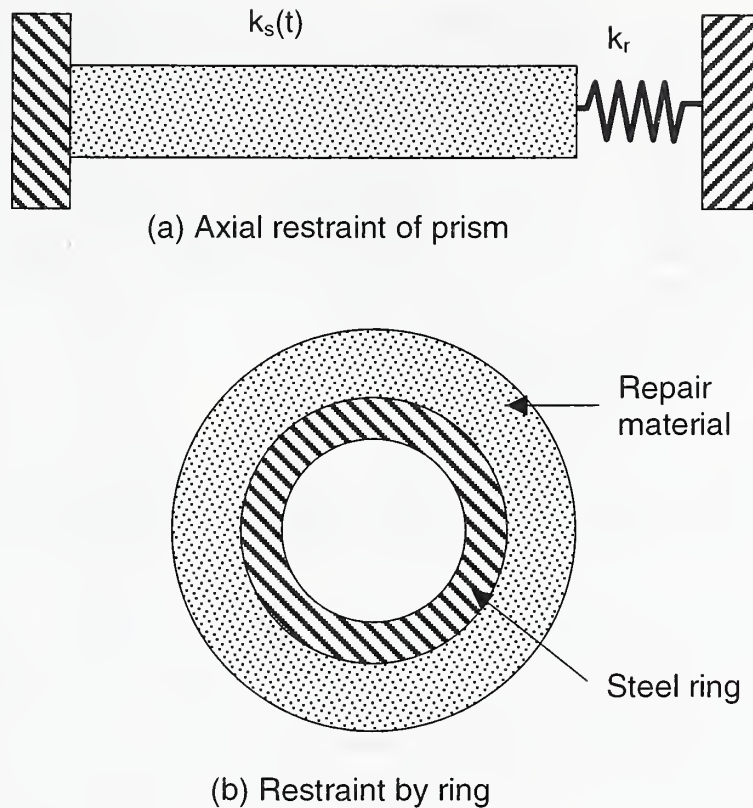Steel ring

(b) Restraint by ring

Figure 2   Restrained shrinkage tests: (a) axial restraint and (b) ring restraint

restraint of a prism, as shown in Fig. 2(a). This would involve the adoption of a standard test frame with fixed stiffness, k_r. A difficulty with this approach is the transfer of the tensile force from the restraining fixture to the specimen. The problem may be overcome by the second type of test, as shown in Fig. 2(b). In this case, an inner steel ring restrains the shrinkage of the outer ring of repair material. The ring of repair material is, in effect, subjected to loading equivalent to a uniform pressure at the interface with the steel ring. This uniform pressure leads to a tensile stress in the circumferential direction and a compressive stress in the radial direction. These stresses vary in magnitude with radial distance, as shown in Fig. 3. For a uniform circumferential shrinkage strain, the critical tension-compression state of stress occurs at the inside radius of the ring of repair material (Shah et al. 1998).

Level 2 model—The next level of modeling would predict the short-term performance of the repair material under anticipated field conditions. In this context, "short term" refers to the time duration after which there are small changes in material properties, and it may include a duration that encompasses one complete cycle of extremes in environmental conditions. The analysis would consider the actual three-dimensional shape of the repair in relation to the base concrete. It would consider not only the stresses within the repair materials but also the conditions at the interface with the
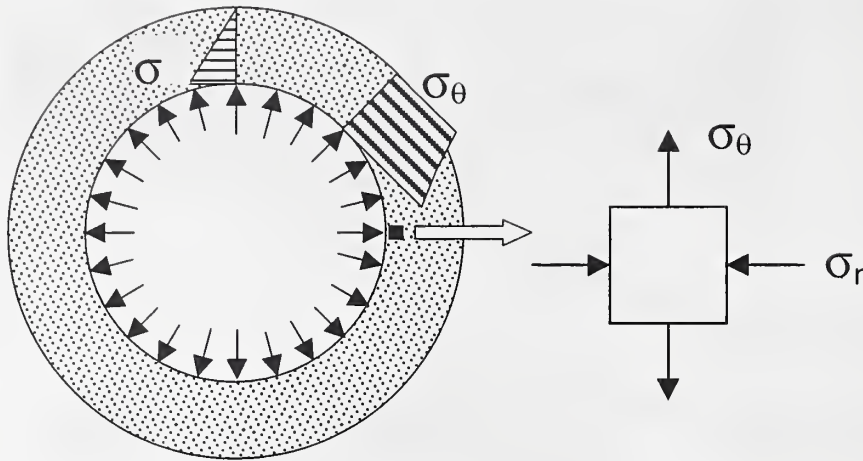
Figure 3   Equivalent uniform pressure loading and biaxial stresses in ring test

substrate. The model would simulate the temperature history of the repair by taking into account the initial temperatures of the substrate and repair material, the heat of hydration, the anticipated ambient conditions, and the effects of insulation (if used). A Level 2 model might rely on some of the techniques used for a Level 1 model, but it would have to include additional capabilities such as moisture transport as affected by the porosity of the repair material and the ambient conditions. As in the case of the Level 1 model, there is a need to determine the very early-age properties of repair materials and how they change as a function of time and temperature (maturity).

Level 3 model—The ultimate goal of a model would be to predict the performance of the repaired structure. It would have to simulate the long-term interaction of the repair with the structure for a given environmental exposure. To standardize some of the parameters that will be used in Level 3 modeling, it will be necessary to define "standard" exposure conditions (such as number of cycles of freezing and thawing, relative humidity and temperature ranges, and presence of deleterious chemicals). It would also be necessary to define the applicable "failure" criterion that signals the end of satisfactory performance. This would in turn require understanding the controlling degradation mechanism (freezing and thawing damage, corrosion, chemical attack, and so forth). Since this level of modeling would involve predictions based on assumptions and simplifications, consideration of the sensitivity of the predictions to the assumed conditions would be essential. Because of this, modeling should be based on stochastic analysis. The output of Level 3 modeling would provide the expected service life (and its confidence interval) of the repaired structure, which would be vital for life cycle cost analyses of alternative repair strategies.

Users

Any model development effort should consider carefully the potential users. Key factors to consider are the quantities needed as model input and the nature of the output. Depending on the user, the required model input can be quite simple or

complex. The model may include sub-models that use simple input values to estimate the material characteristics required to run the main model. In general, the simplicity of the input and output is related to the user's level of understanding of the underlying principles of the model. Thus models intended for practical use by designers and contractors would require simpler input and output interfaces than models intended for researchers. However, complex models could be used to generate useful design tools such as graphs and tables. An example that was cited is the well-known series of graphs used to predict the evaporation rate of a free water surface as a function of ambient conditions.

Existing Models:
The working group identified a number of existing models that have been developed to predict the potential for cracking due to volume changes under restrained conditions. Some have been developed specifically for analyzing repair materials, while others may be modified to make them applicable to modeling concrete repairs. The models that were identified are as follows:

- Conproco procedure (Pinelle 1995)
- ACI Committee 209 procedure (ACI 209R-92) with new Comité International du Béton (CIB) equations for time-dependent properties
- Laval University (Pigeon and Bissonette 1999)
- Chidiac et al. (1997)
- The University of Texas model for polymer concrete repairs[1]
- 4C-Temp & Stress Model (Danish Technical University; Pedersen et al. 1997)
- HIPERPAV (McCullough and Rasmussen 1999)
- Warsaw University of Technology (polymer concrete repairs; Czarnecki et al. 1999)

Most of the above are basically "load-resistance" models that compare the computed stresses in a particular structural configuration with the available strength as a function of time. In addition to these models, a fracture mechanics based model was developed at Northwestern University to analyze the ring test (Shah et al. 1998).

Action Items
The working group concluded its discussion by identifying six action items:

- A synthesis should be carried out of operational Level 1 models. The synthesis should identify the underlying mechanistic model, the required input, assumptions and simplifications that are used, and the nature of the output.
- A comparison of the predictions by the functioning Level 1 models should be carried out. Test problems should be designed that are within the scope of as many models as possible.

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[1] Zalatimo, J.A., and Fowler, D.W., "Designing Durable Polymer Concrete Overlays," manuscript distributed at workshop

- A similar review and synthesis of available Level 2 and Level 3 models should be carried out.
- Experimental studies should be carried out of time-dependent properties of repair materials under tensile stress and comparison with properties measured under compression. These studies should be planned using the principles of experiment design to ensure statistically valid results. This information is vital for determining the standard test methods needed to measure the material properties required as input to numerical models.
- Test methods are needed to measure early-age properties of repair materials. These methods should be reliable, robust, and relatively simple to perform.
- A modeling subcommittee should be established within existing ACI and ICRI committees. The subcommittee will provide a focus for sharing the latest developments and for publication of documents on the state-of-the-art and design practices as they evolve.

Interested parties should seek to establish consortia within the ACI Strategic Development Council to fund needed research.

2.2 Working Group 2 — Repair Design, Specification, and Application

Objectives
The working group discussion was mainly directed to the following topics:

- The practical applicability of the U.S. Army Corps of Engineers (USACE) proposed Performance Criteria for Selection of Repair Materials for Non-Structural (Protective) Repairs (Vaysburd et al. 1999).
- The adoption of the USACE proposed Repair Material Data Sheet Protocol (Vaysburd et al. 1999).
- Test methods for sensitivity to cracking of repair materials.

The ultimate objective of this group's discussion was to identify those properties of cement-based repair materials and the corresponding test methods to provide the basis for a quantitative approach for predicting cracking in concrete repairs and for selection of crack-resistant repair materials. The members agreed that appropriate material properties are critical for crack resistance and durability of concrete repairs, but equally important are the quality of the design and construction practices, which are beyond the scope of the present workshop.

It was recognized that to predict the useful life of repaired structures requires knowledge of more than basic material properties measured under standard conditions. To predict crack related-failures, as a function of the variables involved in repair material systems, requires more knowledge, at a fundamental level, about the complex interrelationships between properties and environment.

Table 1 — Proposed USACE Performance Criteria for the Selection of Repair Materials (Vaysburd et al. 1999)

Property	Test Method	Requirement
Tensile strength, minimum 28 d	CRD-C 164 (WES 1949b)	2.8 MPa (400 psi)
Modulus of elasticity, maximum	ASTM C 469	24 GPa (3.5×10^6 psi)
Coefficient of thermal expansion	CRD-C 39 (WES 1949a)	13 µm/m/°C (7×10^{-6}/°F)
Drying shrinkage, maximum - 28 d - 1 year	ASTM C 157 (1949e) (Modified). For modifications to the standard, see "Data Sheet Protocol," Table 2	400 µm/m 1,000 µm/m
Restrained shrinkage - -cracking - implied strain at 1 year, maximum	Ring Method. For test description, see "Data Sheet Protocol," Table 2	No cracks within 14 d 1,000 µm/m

The working group discussed the proposed USACE performance criteria for the selection of non-structural repair materials (Table 1) and the proposed USACE repair material data sheet protocol (Table 2).

It was recognized that many repair materials presently manufactured do not satisfy the proposed performance criteria. The working group did not reach a consensus on the need and merit of all the performance requirements and test methods. However, it concluded that performance criteria and standard data sheet protocols are necessary and that those proposed by the USACE provide good starting points.

The group noted that the ring test shows promise as an indicator of the cracking tendency of repair materials. Further research has to be focused on factors such as specimen geometry, test instrumentation, and environmental conditions.

Although the USACE study (Vaysburd et al. 1999) did not show definitive correlations between tensile creep, creep relaxation, and crack resistance of the material, it was agreed that tensile creep merits further study in the context of establishing performance criteria. A simplified and reproducible test method for tensile creep of repair materials needs to be developed.

Table 2 — USACE Recommended Repair Material Data Sheet Protocol with Commentary (Vaysburd et al. 1999)

1.	**Repair Material Description**

- Recommended use
- Benefits
- Limitations

2.	**Composition Data**

- Base material(s)

Example: This repair mortar is composed of a precise blend of portland cement, microsilica, graded aggregates, dry acrylic polymer and fine fibers.

- Sulfur trioxide (SO_3), % - ASTM C 563
- Alkali content, kg/m^3 (lbs/yd^3)

The typical means by which the alkali content has been controlled with concrete mixtures in the U.S. has been to establish a maximum limit only on the portland cement. Cement with an alkali content smaller than 0.6 %, expressed as equivalent Na O, is referred to as low alkali cement. This provision proved satisfactory for concrete. The disadvantage of establishing an alkali limit based on the alkali of the portland cement alone for repair materials is that many proprietary repair materials contain blends of different cements, additives, admixtures and other constituents that contain alkali. It is the sum of the alkalis from all sources that is pertinent to the potential reaction with a reactive aggregate.

Past research conducted first in Germany, and then in Canada, led to the conclusion that when the alkali in a mixture is kept below a maximum of 3.0 kg/m^3 (5.0 lbs/yd^2), there will be no ASR (Publication No. FHWA-SA-97-045, Gress, D., "Early Distress of Concrete Pavements," January 1997).

- pH
- Air content

3.	**Physical Properties**

- Unit weight of material, kg/m^3 (lb/ft^3)
- Fresh wet density, kg/m^3 (lb/ft^3) – ASTM C 138
- Strengths

		Age, days			
Property and Test Method		7	3	7	28
Compressive strength					
- Mortar – ASTM C 109					
51 mm (2-in.) cubes					
- Concrete mortar extended with coarse aggregate – ASTM C 39					
76 x 152 mm (3 x 6-in.) cylinders					
Flexural Strength – ASTM C 78					
- Mortar					
- Concrete; mortar extended with coarse aggregate					
Direct tensile strength – CRD-C 164					
- Mortar					
- Concrete; mortar extended with coarse aggregate					

- Modulus of elasticity – ASTM C 469
  - Mortar
  - Concrete; mortar extended with coarse aggregate

4.   Performance Properties

- Drying shrinkage - ASTM C 157 (Modified)

Modifications to ASTM C 157 "Length Change of Hardened Hydraulic Cement Mortar and Concrete":
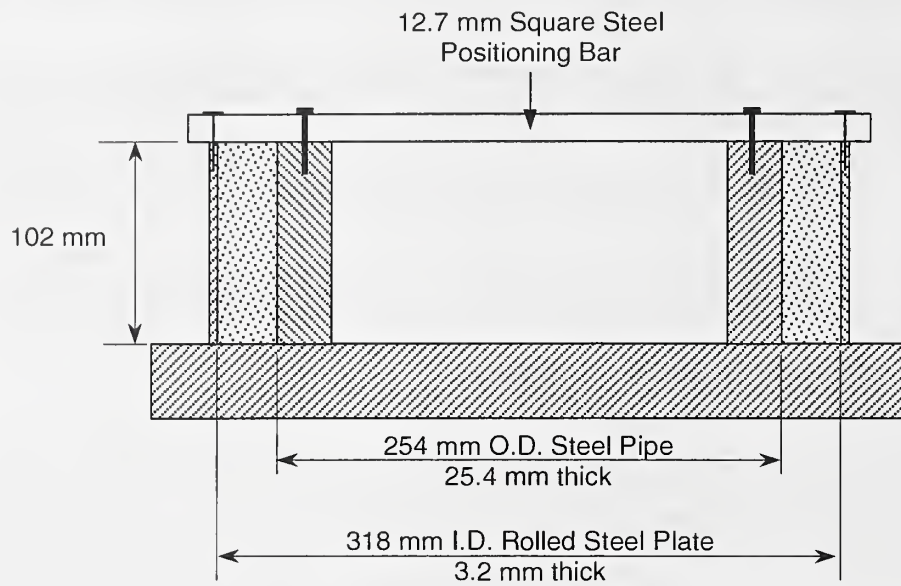*a.   Standard specimen size is 76 x 76 x 275 mm (3 x 3 x 11-¼ in.) for mortar, mortar extended with coarse aggregate, and concrete.*
b.   Remove specimen from mold at 23 ± ½ hours and make initial comparator reading immediately. (For rapid hardening materials, remove specimen from mold at 3 hours and make initial comparator reading).
c.   The specimens are then stored under the standard conditions of 23.0 ± 1.7°C (73.4 ± 3°C) and 50 ± 4 % RH.

Subsequent comparator readings are to be taken at ages of 3 days, 7 days, 14 days, 1 month, and 2 months; measurements shall continue until 90 % of ultimate drying shrinkage is reached. Ultimate shrinkage is to be determined as described in ASTM C 596, Drying Shrinkage of Mortar Containing Portland Cement.
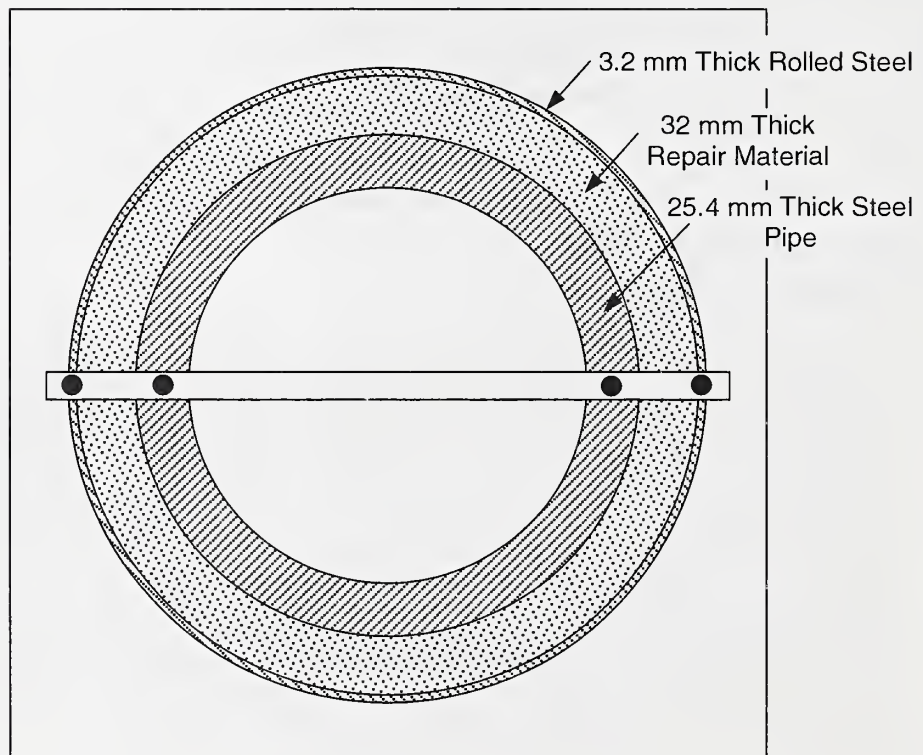
   - Mortar
   - Concrete; mortar extended with coarse aggregate

- Coefficient of thermal expansion – CRD C 39
   - Mortar
   - Concrete; mortar extended with coarse aggregate
- Freezing and thawing resistance – ASTM C 666 (Procedure A)
- Compressive creep – ASTM C 512
   - Mortar
   - Concrete; mortar extended with coarse aggregate
- Rapid chloride permeability – ASTM C 1202
   - Mortar
   - Concrete; mortar extended with coarse aggregate
- Sulfate resistance – ASTM C 1012
- Cracking resistance – Ring Test (see description below)
   - Age at first crack
   - Implied strain
     (Sum of average crack widths at the end of test divided by the ring circumference)
   - Age at the end of the test

Description of the Ring Test

This method allows the determination of a material's sensitivity to cracking caused by restrained volume changes. Figure A shows the mold and specimen for the ring test. The material is cast around a 254-mm (10-in.) outside diameter and 25.4 mm (1 in.) thick steel pipe. The thickness of the tested material ring is 32 mm (1.25-in) and the height is 102 mm (4 in.). The freshly-mixed material should be consolidated in the mold as recommended by the manufacturer. The material rings are to be kept in their molds and covered with plastic for the first 24 hours after they are cast. After removal of the outer rings of the molds, the top surfaces of the material rings should be sealed with epoxy (the rings are not removed from the bottom plates of the molds). The material rings should then be wet cured for 48 hours. After the completion of the recommended curing period, the specimens shall be kept for at least 60 days under standard laboratory conditions of 23.0 °C ± 1.7 °C (73.4 °F ± 3°F) and 50 % ± 4 % RH. The rings should be monitored daily for evidence of cracking. The day that cracking is observed should be recorded and the initial crack width should be measured and recorded to the nearest 0.02 mm (0.001 in). The width of each crack should be measured periodically at the quarter points and mid-height along the crack, and the average width should be recorded. The computed strain, or implied strain, associated with the crack widths at the end of testing is reported in the data sheet. The implied strain is computed by taking the sum of the average crack widths of all cracks in the specimen and dividing by the ring circumference – approximately 1000 mm (39.4 in.)

12.7 mm Square Steel
Positioning Bar

102 mm

254 mm O.D. Steel Pipe
25.4 mm thick

318 mm I.D. Rolled Steel Plate
3.2 mm thick

SECTION

3.2 mm Thick Rolled Steel

32 mm Thick
Repair Material

25.4 mm Thick Steel
Pipe

PLAN

Figure A. Ring test mold and test specimen

Cracking resistance – German Angle Test (modified)
- Age at first crack
- Number and average width of cracks at end of test

Description of the German Angle Test

This test was originally developed by the Technical Academy, Aachen, Germany and was adopted by the Highway Construction Department of the German Federal Ministry of Transport as part of the Technical Test Regulations (TR BE-PCC) for concrete substitution systems made of cement mortar or concrete with a plastic additive. The mold and specimen used for this test are shown in Figure B.

The following is the modification of this test:

Apply epoxy bonding compound before placing repair mixture into the angle. Unless the manufacturer recommends otherwise, the mixture is to be compacted by external vibration, and then leveled off and smoothed. The specimen should be wet cured for 72 hours, then stored under the intended service conditions, or stored in the laboratory under conditions that simulate intended service conditions. Conditions of the test shall be described in the data sheet. The specimens shall be monitored for cracking for at least 90 days. The time to cracking, number of cracks at the end of the test, and average crack width should be recorded.
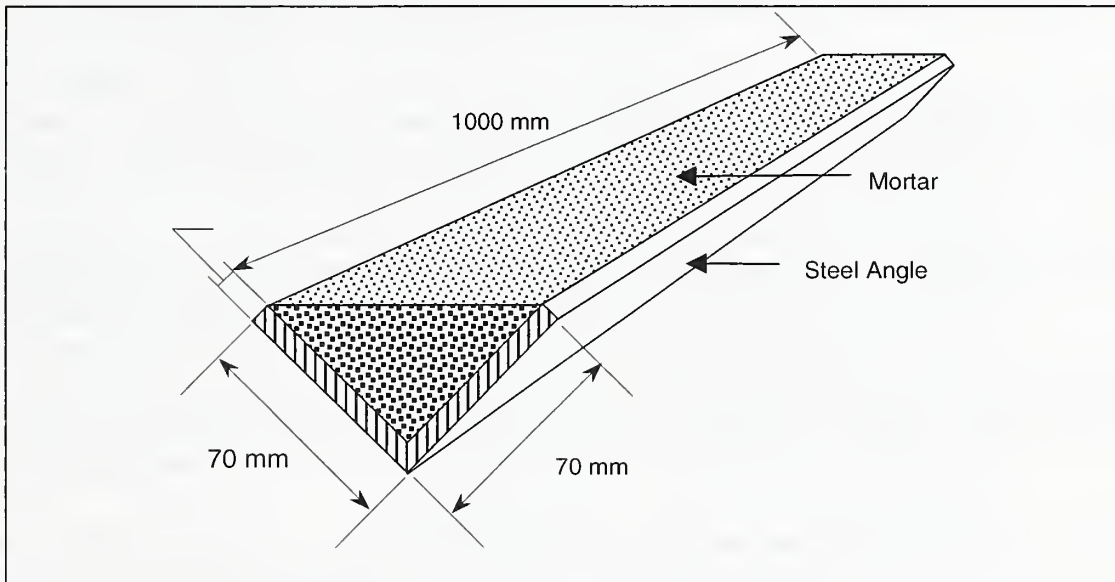
Figure B. German Angle Test specimen

5.	**Packaging, storage**
	• Packaging • Volume yield • Shelf life • Storage requirements
6.	**How the Material Works**
	Example: This product is a medium slump, two-component, trowel grade mortar. The product's portland cement base and low water-to-cement ratio provide the foundation for the system's strength, durability and basic physical properties. To improve its properties, the product utilizes the advantages of an acrylic polymer emulsion. The fine particle size of the acrylic emulsion allows it to penetrate and form a polymer film throughout the C-S-H matrix and microvoids. This filling of the voids reduces shrinkage, permeability and moisture absorption. Additionally, the polymer increases adhesion, flexibility, and freeze-thaw and abrasion resistance.
7.	**How to Use the Material**
	• Concrete surface preparation • Mixing • Application and finish • Curing • Cleanup • Safety

A consensus was reached that the proposed performance criteria are only for protective (non-structural) repairs. Performance criteria for structural, load-carrying repairs need to be developed. A feedback mechanism and database need to be established to evaluate the merits of the proposed criteria in practice.

It was noted that research at Laval University is also directed to the development of performance criteria and test methods. A technology transfer mechanism is urgently needed to review the research results and ensure timely implementation. The International Concrete Repair Institute (ICRI) and others should provide the leadership role to establish this mechanism.

Action Items:
In conclusion, the working group identified the following action items:

- The development of performance criteria for structural repairs should be carried out. ACI and ICRI should take the leadership in this direction. Interested parties should consider the establishment of a partnership or consortia to fund the needed research.
- Test methods are needed to measure the sensitivity to cracking of repair materials. The methods should be reliable, short-term, and reproducible.
- ICRI should consider including the USACE performance criteria for protective repair materials and the recommended material data sheet protocol in their consensus guidelines.
- The ring test method and Structural Preservation Systems, Inc. stress/strain indicator technique should be further researched as a practical procedure to evaluate crack resistance of repair materials.
- A centralized technology transfer mechanism needs to be established to review, coordinate the research, and publish the results as they develop.
- A joint repair materials committee or subcommittee should be considered within ICRI and ACI to focus on issues discussed by the Workshop.

2.3 Working Group 3 — Repair Materials and Systems

Objectives
The group's discussion focused mainly on addressing the following questions:

- What are the critical material properties affecting cracking in concrete repairs?
- How to design a test method for predicting a material's in-place performance considering all variables involved in field applications?
- How to define standards for the evaluation of material performance in a selected test?

There is presently no generally accepted test method or methods to determine the long-term performance of a material to be used for surface repairs. The most important

material properties in this respect are likely to be those related to the various types of deformation: shrinkage, creep, modulus of elasticity, and coefficient of thermal expansion. However, there is no agreement on the relative influence of each of these properties. Furthermore, there are insufficient field and laboratory data, both on the properties of repair materials and on the performance of repaired elements subjected to different exposures, to correlate any single property or a combination of these properties to observed long-term field performance.

After an open discussion on the subject, the members of the working group agreed on a number of basic points:

- Considering the complexity of the problem and all the variables involved (material properties, substrate properties, exposure conditions, etc.), it will take many years before a sound design method based on theoretical considerations as well as empirical relationships is developed.
- Industry, both for marketing purposes and for construction, needs relatively simple test methods that can be easily used, and, better still, a unique method that would generate one single index or value describing the expected durability, that is, a "number."
- Any test method or design method will have to take into account the variability of the exposure conditions (variations in relative humidity and temperature, with or without freezing).
- The basic material properties (mechanical, thermal, visco-elastic, and shrinkage) will always be required for characterization purposes and modeling, and will, therefore, always have to be measured using standardized procedures.

In view of the above, and considering the urgent need for more rational design methods in the field of surface repairs, the members of the working group discussed a standardized test method that would rapidly yield sound information on the long-term performance of a given repair material subjected to various types of exposure conditions. It was agreed that such a test method would necessarily have to use a composite specimen in order to represent as much as possible the actual conditions under which repair materials are placed. Test specimens should also be sufficiently small in order to be suitable for both laboratory and field testing. The test should allow the influence of various exposure conditions to be investigated. Like any other test method, it should be repeatable, and it should be designed to ensure that both the material and the application method adequately represent what occurs in the field.

A number of points concerning the scope of the required test method were discussed and agreed upon. It was decided that only materials with proper rheology, suitable for the intended environment, free of early-age problems, properly cured, well bonded to the substrate, and non load bearing should be tested with this method. It was also agreed that the relative thickness of the surface repair was the most significant geometrical parameter, since the basic problem is one of restrained shrinkage, and the

repair thickness has a large influence on the overall shrinkage of the repair layer. The test method should not be intended to simulate various patch shapes, because the test results in terms of cracking would then be too complex to analyze and comparisons between different test results would be difficult.

The working group considered the "box test," used in the USACE field study (Emmons et al. 1998), to be the type of test needed, although, as previously mentioned, the test specimen would have to be sufficiently small to allow it to be used also in the laboratory. The test specimen used in the USACE field study is shown in Fig. 4; it is a precast concrete slab with a cavity to be filled with the repair material. The bottom of the cavity contains grooves to provide mechanical interlock between the repair material and substrate. This test could be used to generate laboratory and field data, under known exposure conditions, which could then be correlated to observed field performance, using whatever possible basic material properties and models. One of the interesting possibilities with such a test would be to measure the performance of a reference material under various types of exposure conditions, and then correlate, as just mentioned, the results obtained with the observed field performance. Such a standardized test method would allow the development of a database from both laboratory and field tests under known exposure conditions, including, when available, the relationships with observed field performance.

The members of the working group suggested that a small number of persons be selected and given the task of defining precisely the required characteristics of the "box test" before considering its standardization. In addition to the size of the box, it will be necessary to define exactly the preparation of the substrate, since absorption of water by the substrate can influence the characteristics of the interface and the performance of the repair material. It will also be necessary to define standards for the evaluation of performance (type and intensity of cracking as a function of time of appearance), including the possibility of in-place tests (such as a pull-out test) to evaluate the residual mechanical strength.

At the conclusion of the workshop, representatives from Conproco, the Corps of Engineers, Structural Preservation Systems, and Laval University agreed to meet in the near future to outline the scope of work to be done for further development of the "box test." A major part of this work could be performed by the Industrial Chair on Shotcrete and Concrete Repairs at Laval University, which has an objective to provide technical support to the concrete repair industry.

In addition to the development of a field performance test, it was suggested that one of the most important ways to improve the durability of surface repairs would be to disseminate as much information as possible, in the following areas:

- Available test data (both field and laboratory);
- On-going and planned studies; and
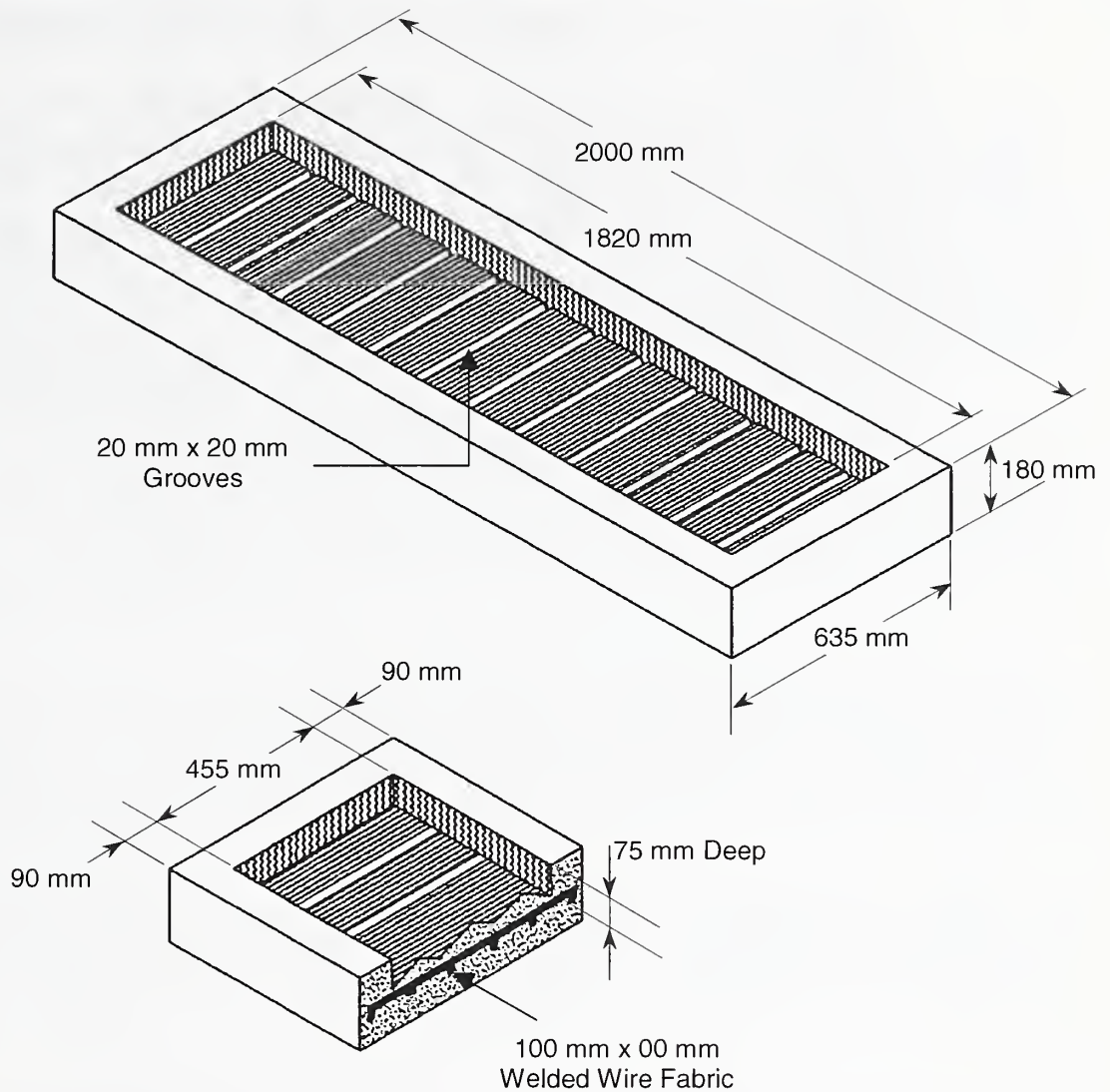
Figure 4   Precast concrete slab with 75 mm deep cavity to evaluate the field cracking performance of repair material (Emmons et al. 1998)

- Current and new types of repair materials available.

This could be done through ICRI. It is vital to remember that many, if not most, of the surface repair durability problems observed in the field are due to improper selection and use of repair materials.

Action Items
The working group concluded its report by highlighting four action items:

- A simple test method is needed that can be used easily under different exposure conditions. The method should account for all in-situ variables, and

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should be able to generate one single value or index describing the expected performance.

- The "box test" developed by Structural Preservation Systems, Inc. and described in the Corps of Engineers report (Emmons et al. 1998) should be studied to define precisely the required characteristics of the test. The test should be modified as needed and considered for development as a standard test method.
- Interested parties should consider establishing consortia to join their efforts and fund needed studies.
- Dissemination of information on field and laboratory test data for current and new repair materials, and on ongoing research studies in the concrete repair field. This could be implemented through ICRI.

3. SUMMARY AND RECOMMENDED ACTIONS

In the course of their discussions, the three working groups, especially Groups 2 and 3, found that their approaches to dealing with these challenges often were similar. In some circumstances, the working group discussions revealed that, although the participants share similar concerns, they proposed different approaches for addressing the same challenges. This reflects the different perspectives and expertise of the participants and highlights the need for a regular exchange of opinions. These exchanges provide opportunities to further coordinate and consolidate activities to improve the quality of the concrete repair industry.

In brief, this workshop yielded a high quality attack on the problem of cracking of concrete repairs. While it proved to be difficult to arrive at quantitative conclusions, nonetheless, most of the critical issues were defined. This summary of the workshop should provide useful information to those already working in this field, as well as to those entering it for the first time.

To succeed, the concrete repair industry will need to change attitudes toward research, design, material manufacture, construction, quality control, and education. The action plan resulting from this workshop is a step in this direction, providing a list of necessary tasks to be undertaken and serving as a catalyst for improvements in the concrete repair industry.

Enhancing the industry knowledge base is essential for appropriate design and construction and to make sound decisions. This activity requires creating improved mechanisms to share the knowledge that is available, as well as developing additional knowledge.

The following short-term action items, in addition to the items emphasized in the working group discussions, were adopted at the plenary session of the 1999 Workshop:

- A test method for evaluating the field performance of concrete repair materials is to be designed, evaluated, and introduced into practice by a partnership of the following organizations:
    - Laval University
    - U.S. Army Corps of Engineers
    - Structural Preservation Systems, Inc.
    - Conproco, Corp.
    - Sika Corp.
- Organize a joint ICRI/ACI Repair and Rehabilitation Task Force (RRTF) to address and coordinate issues related to performance of concrete repairs.
- Proceed with establishing consensus "Performance Criteria for Selection of Repair Materials" and a standard "Repair Material Data Sheet Protocol" (ICRI/ACI RRTF)

- Establish a centralized site for compilation and storage of performance data on repair materials (USACE, NIST, Laval University). The ACI Concrete Research Council (CRC) may provide funding.
- Develop guidelines on the use of ring test method to evaluate resistance to cracking of repair materials (ICRI).
- Organize a Symposium on Performance of Repair Materials during the 2001 ICRI International Congress.
- The next workshop, with the theme "Improving the Performance of Concrete Repairs," will take place in 2001, in Quebec, Canada.

The 1999 Workshop speaks directly to the concrete repair community: to the owners, designers, and contractors; to manufacturers; to research laboratories; to universities; to professional societies and trade associations. This workshop summary also speaks to the government agencies who have responsibilities to help provide quality public structures for their citizens.

Finally, the discussions and summary of this workshop do not give the final solution for predicting the field performance of concrete repairs. However, they do delineate the critical issues that must be addressed to reach such a solution. It is hoped that subsequent work will benefit from this workshop.

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APPENDIX A

WORKSHOP PROGRAM

WORKSHOP ON PREDICTING THE PERFORMANCE
OF CONCRETE REPAIR MATERIALS

April 26 and 27, 1999
New England Conference Center and Hotel
Durham, New Hampshire

DAY 1

7:15 AM	Registration	
7:30 AM	Continental Breakfast	
	General Session	*Chairman: David Fowler* *The University of Texas*
8:00 AM	Welcome and Review of the Workshop Goals	*Christopher Brown* *Conproco, Corp.*
8:10 AM	Welcome	*Noel Mailvaganam* *NRC Canada*
8:15 AM	An Overview of the Research Study, "Performance Criteria for Selection of Repair Materials"	*Jim McDonald* *U.S. Army Corps of Engineers*
8:20 AM	"Performance Criteria for Selection of Repair Materials: Laboratory Testing"	*Randall Poston* *WDP Associates*
8:50 AM	"Performance Criteria for Selection of Repair Materials: Field Testing"	*Alexander Vaysburd* *Structural Preservation Systems*
9:20 AM	"Performance Criteria for Selection of Repair Materials: Summary"	*Jim McDonald* *U.S. Army Corps of Engineers*
9:50 AM	Coffee Break	
10:00 AM	"Considerations on the Dimensional Compatibility of Concrete Repairs"	*Benoît Bissonnette* *Laval University*

10:30 AM	"Modeling the Short- and Long-Term Behavior of Concrete Repair"	*Samir Chidiac* *Chidiac & Associates*
11:00 AM	"Modeling Dimensional Behavior of Repair Materials"	*Dennis Pinelle* *Conproco, Corp.*
11:30 AM	"Premature Cracking in Reconstructed Concrete Bridge Barrier Walls"	*Daniel Cusson and* *Wellington Repette* *IRC/CNRC*
12:00 PM	"Methods for Crack Prediction of Cementitious Repair Materials"	*David Scott* *U.S. Army Corps of Engineers*
12:35 PM	Lunch	
1:40 PM	Instructions to Working Groups	*Alexander Vaysburd* *Structural Preservation Systems*
1:50 PM	Break	
2:00 PM	Working Group Discussions	
5:00 PM	Adjournment	

DAY 2

7:30 AM	Continental Breakfast	
8:00 AM	Working Group Discussions	
10:00 AM	Conproco Plant Tour	*Dennis Pinelle* *Conproco, Corp.*
12:00 PM	Lunch	
1:00 PM	Plenary Session Reports from Chairs of Working Groups	***Chairman: Peter Emmons*** ***Structural Preservation Systems***
2:30 PM	Final Discussions and Recommendations for Action	
3:00 PM	Adjournment	

APPENDIX B

WORKSHOP PARTICIPANTS

AND WORKING GROUP MEMBERS

WORKSHOP PARTICIPANTS

| Name	Company
Benoît Bissonnette	Laval University, Canada
Christopher Brown	Conproco, Corp.
Douglas Burke	Naval Facilities Engineering Service Center
Nicholas Carino	NIST
Samir Chidiac	Chidiac & Associates
Ian Christopher	Conproco, Corp.
Milt Collins	ICRI
Daniel Cusson	NRC Canada
Peter Emmons	Structural Preservation Systems
David Fowler	The University of Texas
Tim Gillespie	Sika Corporation
Paul Kelley	Simpson, Gumpertz and Heger
Noel Mailvaganam	NRC Canada
Beatrice Martin-Perez	NRC Canada
David McDonald	U.S. Gypsum
James McDonald	U.S. Army Corps of Engineers
Rod Meyers	Master Builders, Inc.
Matt Miltenberger	Master Builders, Inc.
Christopher Piecos	Five Star Industries
Michel Pigeon	Laval University, Canada
Dennis Pinelle	Conproco, Corp.
Randall Poston	WDP & Associates
Gajanan Sabnis	Howard University
David Scott	U.S. Army Corps of Engineers
Heather See	Master Builders, Inc.
Ken Snyder	NIST
Paul Tourney	W.R. Grace & Co.
Alexander Vaysburd	Structural Preservation Systems
James Warner	Consultant
Daniel Webber	NY/NJ Port Authority

Workshop Participants at Opening Session

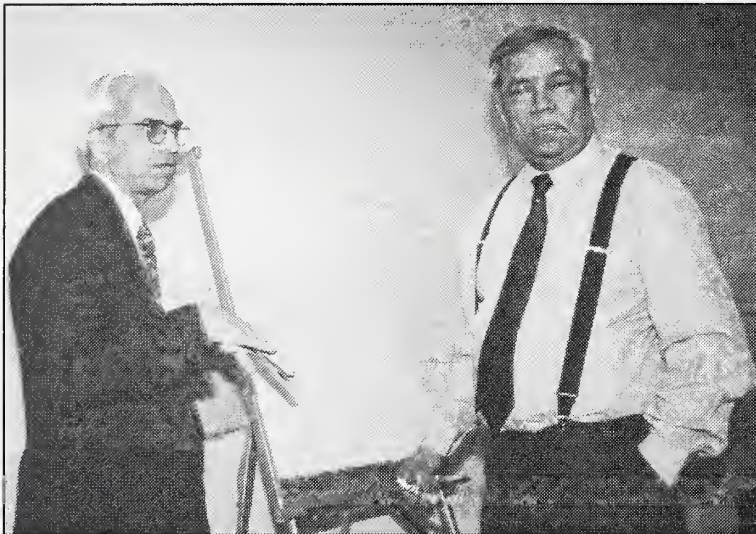Dennis Pinelle hosts tour of Conproco Laboratory
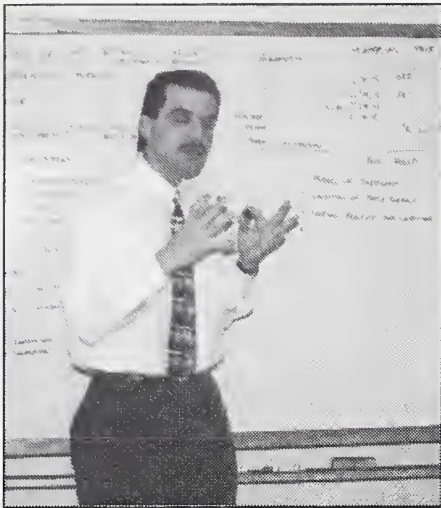
Samir Chidiac during Working
Group 1 discussion

David McDonald during Working
Group 3 discussion

Gajanan Sabnis (L) and
Noel Mailvaganam (R)
during Working Group 3
discussion

Heather See, Chris Brown, and David Fowler (L to R) during Working
Group 3 discussion

WORKING GROUP 1

MODELING

Chairman: Nicholas Carino, NIST, USA
Co-chairman: Beatrice Martin-Perez, NRC, Canada

Benoît Bissonnette	Laval University, Canada
Samir Chidiac	Chidiac & Associates, Canada
Ian Christopher	Conproco, Corp., USA
Rod Meyers	Master Builders, Inc., USA
Matt Miltenberger	Master Builders, Inc., USA
Dennis Pinelle	Conproco, Corp., USA
David Scott	U.S. Army Corps of Engineers, USA
Ken Snyder	NIST, USA
Paul Tourney	W.R. Grace & Co., USA

WORKING GROUP 2

REPAIR, DESIGN, SPECIFICATION AND APPLICATION
(USERS OF REPAIR MATERIALS)

Chairman: Randall Poston, WDP & Associates, USA
Co-chairman: Alexander Vaysburd, Structural Preservation Systems, Inc., USA

Douglas Burke	Naval Facilities Engineering Service Center, USA
Daniel Cusson	NRC, Canada
Peter Emmons	Structural Preservation Systems, USA
Paul Kelley	Simpson, Gumpertz and Heger, USA
James McDonald	U.S. Army Corps of Engineers, USA
James Warner	Consultant, USA
Daniel Webber	NY/NJ Port Authority, USA

WORKING GROUP 3

REPAIR MATERIALS AND SYSTEMS
(MATERIAL MANUFACTURERS AND RESEARCHERS)

Chairman: Michel Pigeon, University of Laval, Canada
Co-chairman: Tim Gillespie, Sika Corp., USA

Christopher Brown	Conproco, Corp., USA
Milt Collins	ICRI, USA
David Fowler	The University of Texas, USA
Noel Mailvaganam	NRC, Canada
David McDonald	U.S. Gypsum, USA
Christopher Piecos	Five Star Industries, USA
Gajanan Sabnis	Howard University, USA
Heather See	Master Builders, Inc., USA